Quadrature-Squeezed Light Detection Using a Self-Generated Matched Local Oscillator

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A local oscillator (LO) which can correctly decode the spatiotemporally distorted quadrature-squeezed light generated by means of single-pass traveling-wave optical parametric amplification is experimentally demonstrated. Such a matched LO is automatically produced in our squeezed-light generation scheme. With the matched LO 5.8 ± 0.2 dB [$(74 \pm 1)\%$] of quadrature squeezing is observed which, to the best of the authors' knowledge, is the highest observed in any traveling-wave squeezing experiment to date.

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Recent quadrature-squeezing experiments have shown a great deal of improvement in the amount of observed quantum-noise reduction over the earlier experiments [1]. For example, the cw squeezed light generated from a subthreshold optical parametric oscillator—a standing-wave intracavity optical parametric amplifier (OPA)—resulted in 6.0 dB (75%) of noise reduction [2], and 5.1 dB (69%) of pulsed squeezing was observed in traveling-wave fiber ring experiments [3]. However, the pulsed squeezed light generated from a single-pass traveling-wave OPA has not yielded more than 2 dB (37%) of noise reduction, despite the number of attempts in several laboratories around the world [4–10]. This is rather puzzling in light of the fact that the intensity noises of the signal and idler beams at the output of the same OPA have been demonstrated to be highly correlated [11]. When the two beams were direct detected, the difference-photocurrent noise fell below the shot-noise limit by as much as 7 dB (80%). Moreover, when the signal-beam frequency was up-converted subshot noise quantum correlations could be observed between the idler and up-converted beams, thus demonstrating the phenomenon of quantum frequency conversion [12]. To observe quadrature squeezing all one has to do is to combine the output signal and idler beams on a 50/50 beam splitter and homodyne detect the resulting squeezed beams.

The main reason for not observing a high degree of quadrature squeezing, we believe, is that a local oscillator (LO) with Gaussian spatial profile was employed in all the above experiments [4–10]. To achieve large squeezing the traveling-wave OPA must be operated in the high-gain regime. However, since the experiments are performed with Gaussian beams, in the high-gain regime the quadrature components of the signal field are significantly affected by the pump-field spatial profile [13]. As the pump and signal fields copropagate in the nonlinear medium, due to the phenomenon of gain-induced diffraction [14], the phase fronts of the resulting squeezed beam get distorted, and they do not spatially match with those of the Gaussian LO beam. Such an LO, therefore, cannot detect the squeezed quadrature correctly over the whole beam area. In the standing-wave intracavity or the traveling-wave fiber experiments [2,3] the spatial filtering effect due to the cavity or the fiber substantially alleviates the distortion, and the resulting squeezing profile matches well with a Gaussian LO. Gain-induced diffraction also limits the mean-field deamplification response of a traveling-wave OPA. Consistent with theoretical predictions, the signal-field deamplification in our experiment is limited to $\simeq 3$ dB only, whereas the amplification can easily be >20 dB [14].

In pulsed squeezing experiments [3–10] the signal field is distorted temporally as well. This is because the parametric gain, which depends on the pump-field intensity, is larger in the central portion of the signal pulse, due to higher intensity of the pump pulse, than in the wings. Therefore, if the signal, pump, and LO beams are derived from the same laser, as is the case in the experiments cited above, then the generated squeezed pulse does not mode match with the LO pulse. In the present experiment, however, pulsed homodyne measurement with the matched LO projects out the correct temporal mode as well. This is because the matched LO is generated from the same pump pulse that creates the squeezed pulse.

A parametrically amplified and then attenuated Gaussian beam was tested as a matched LO in an earlier experiment [8]. However, the observation of more than 2 dB of quadrature squeezing was prohibited by the uncontrollable LO phase fluctuations. The phase fluctuations were present because the LO beam was generated from a separate OPA. Recently, we have proposed a novel OPA configuration for quadrature-squeezing generation that automatically produces a spatiotemporally matched LO [15]. In this Letter, we report on the experimental realization of this configuration. Up to 5.8 ± 0.2 dB [$(74 \pm 1)\%$] of quadrature squeezing is observed which, to the best of the authors' knowledge, is the highest observed in any traveling-wave squeezing experiment to date. The squeezing limitation predicted in Ref. [13], which is based on the Gaussian-LO assumption, is clearly circumvented in our experiment.

Our squeezing and matched LO generation scheme is sketched in Fig. 1(a). The signal and idler outputs

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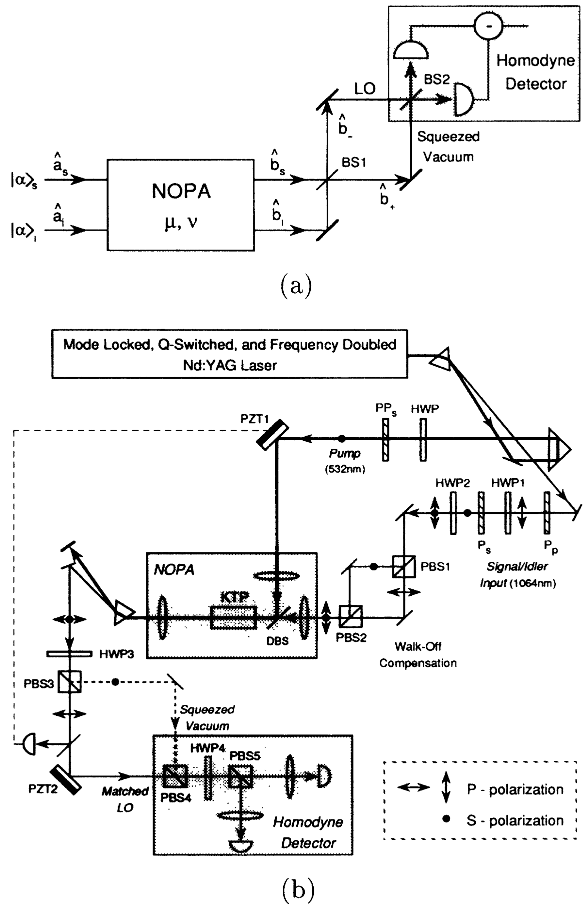

FIG. 1. (a) Scheme for the simultaneous generation of squeezed vacuum and a matched LO. For identical coherent-state inputs ($|\alpha\rangle_s$ and $|\alpha\rangle_i$), adjusting the signal/idler path difference for maximum interference at BS1 creates squeezed vacuum in the destructive interference port and a squeezed-coherent state in the other port. The latter serves as our matched LO. (b) Detailed schematic of the experimental setup to realize the scheme in (a). The signal and idler beams overlap in the NOPA and are distinguished by their orthogonal polarizations. HWP3 and PBS3 together form the 50/50 beam splitter for the orthogonally polarized signal/idler beams. The dotted line represents the electronic feedback loop that locks the pump phase for maximum DOPA gain during the measurement.

of a nondegenerate optical parametric amplifier (NOPA) interfere with each other at a 50/50 beam splitter (BS1). The NOPA outputs are the so-called twin beams which can be described by the Bogoliubov transformations [11] $\hat{b}_s = \mu\hat{a}_s + \nu\hat{a}_i^\dagger$ and $\hat{b}_i = \mu\hat{a}_i + \nu\hat{a}_s^\dagger$, where $\hat{a}_{s(i)}$ is the annihilation operator for input signal (idler) beam and $\hat{b}_{s(i)}$ is that for the output, and $|\mu|^2$ with $|\mu|^2 - |\nu|^2 = 1$ is the NOPA gain. The BS1 mixes the output modes as $\hat{b}_\pm = (\hat{b}_s \pm \hat{b}_i)/2^{1/2}$, and by choosing a suitable path-length difference one obtains

$$\hat{b}_\pm = \mu\hat{a}_\pm \pm \nu\hat{a}_\pm^\dagger, \quad (1)$$

where $\hat{a}_\pm \equiv (\hat{a}_s \pm \hat{a}_i)/2^{1/2}$. From the above equation it is clear that a NOPA with a beam splitter is equivalent to two independent degenerate optical parametric amplifiers (DOPA's). For a balanced input state $|\Psi\rangle \equiv |\alpha\rangle_s|\alpha\rangle_i = |\sqrt{2}\alpha\rangle_+|0\rangle_-$, the output at BS1 is such that $\hat{b}_-$ is in a squeezed-vacuum state, and $\hat{b}_+$ is in a squeezed-coherent state. The latter serves as our matched LO. Since the two DOPA's share the same pump beam, the spatial distortions on the two are expected to be the same, and the LO should project out the proper squeezed mode.

In the homodyne detection of quadrature squeezing one generally uses a coherent-state LO. In our scheme, however, the parametrically amplified LO is in a squeezed-coherent state, which in direct detection is much noisier than a coherent state of the same mean field. Nevertheless, if the dual-detector balanced homodyne scheme [16] is used [BS2 is a 50/50 beam splitter in Fig. 1(a)], the LO noise cancels out [17], and quadrature noise of the squeezed-vacuum mode $\hat{b}_-$ can be detected. When $|\alpha| \gg |\mu|$ the homodyne photocurrent noise variance is $\langle\Delta I^2\rangle \propto 2|\alpha|^2(|\mu| + |\nu|)^2[|\mu|^2 + |\nu|^2 + 2|\mu\nu|\cos(2\phi)]$, where ϕ is the LO phase. The vacuum-state noise variance obtained by blocking the squeezed branch is $\langle\Delta I^2\rangle_v \propto 2|\alpha|^2(|\mu| + |\nu|)^2 = 2|\alpha|^2 g_m$, where $g_m \equiv (|\mu| + |\nu|)^2$ is the DOPA gain. Because of our use of the balanced homodyne scheme [16] the above vacuum-state noise variance is at the coherent-state limit for the incident LO mean field. The quadrature squeezing, therefore, is given by $S \equiv \langle\Delta I^2\rangle_{\phi=\pi/2}/\langle\Delta I^2\rangle_v = 1/g_m$. When the overall detection efficiency (including optical losses, remnant mismatch of the squeezed-vacuum and LO modes, and photodetector quantum efficiencies) η is included, the observed quadrature squeezing is modified to

$$S = 1 - \eta + \eta/g_m. \quad (2)$$

Here we emphasize that the derivation of Eqs. (1) and (2) assumes that the various modes are plane waves. As shown below, the quadrature squeezing measured in our experiment closely follows Eq. (2), verifying that the LO projects out the proper squeezed mode.

In Fig. 1(a) the two 50/50 beam splitters (BS1 and BS2) can also be regarded as forming a Mach-Zehnder interferometer (MZI). Such an arrangement was also used in the fourth-order interference experiments of Rarity *et al.* [18]. However, the inputs to the MZI here are not the paired two-photon states $|1,1\rangle_n$, but the correlated twin beams [11] generated from the NOPA with nonvacuum coherent-state inputs. Also, the path lengths of the twin beams are adjusted and fixed to produce maximum destructive interference for generating the squeezed-vacuum state at BS1.

Figure 1(b) is the sketch of our experimental setup that realizes the scheme in Fig. 1(a). The signal and idler beams overlap in the NOPA, and they are distinguished by their orthogonal polarizations. Many details of the experiment are similar to those given in Ref. [14]. In summary, a mode-locked, *Q*-switched, and frequency-doubled Nd-doped yttrium-aluminum-garnet (Nd:YAG) laser (Quantronix, model 416) produces 1064 nm (IR) and 532 nm (green) pulses to provide the signal and idler (modes $\hat{a}_s$ and $\hat{a}_i$) beams and the pump beam, respectively, to the NOPA. The repetition rates of the Q switch and the mode locker are 1.1 kHz and 100 MHz, respectively. The rf power to the Q switch is adjusted to set a prelase time of 250 μs. The resulting Q-switch envelopes are 150 and 270 ns in duration, and the mode-locked pulses underneath the Q-switch envelopes are $\simeq$140 and $\simeq$200 ps long for the green and IR beams, respectively. The traveling-wave NOPA, which is frequency degenerate but polarization nondegenerate, consists of a type-II critically phase-matched $KTiOPO_4$ (KTP) crystal. The intensity and polarization of the IR pulses from the laser are adjusted, with the use of half-wave plates (HWP1 and HWP2) and polarizers (P_s and P_p), in such a way that the orthogonally polarized signal and idler input pulses to the NOPA are equal in amplitude and in phase with each other. Before the signal and idler beams enter the NOPA, they are separated and recombined with the use of polarizing beam splitters (PBS1 and PBS2) to precompensate for the walk-off that occurs in the KTP crystal due to the critical nature of phase matching. This precompensation improves the extinction ratio from 10:1 to >160 : 1 at PBS3. The intensity of the pump beam is adjusted using a half-wave plate (HWP) and a polarizer (PP_s) and interferometrically aligned with the input signal and idler beams through the dichroic beam splitter (DBS). The phase of the pump pulses, relative to the input signal and idler pulses, is adjusted using a piezoelectric transducer (PZT1) to obtain maximum intensity gain for the signal and idler twin beams at the NOPA output. After dispersing the pump away, the twin beams are mixed using HWP3 and PBS3 to yield a squeezed-vacuum state beam and a matched LO beam as shown in Fig. 1(b). PBS4, HWP4, and PBS5 constitute a 50/50 beam splitter for the balanced homodyne detection of the squeezed vacuum with the matched LO.

About 8% of the LO beam is split off and direct detected to provide a feedback signal for locking the pump phase by moving a mirror that is mounted on PZT1. The feedback controller, not shown in Fig. 1(b), performs a steepest-decent algorithm to lock the pump phase in such a way that the DOPA gain is maximized. The gain fluctuations are maintained to less than 5% throughout the experiment. The LO phase is scanned or locked by moving the mirror mounted on PZT2 which is controlled by a computer. The extinction ratio at PBS4 is > 160 : 1 which ensures that the efficiency of homodyne detection is > 0.987. The currents of the two InGaAs *p-i-n* photodiodes are subtracted and fed into the detection electronics which picks up the noise power at 27 MHz with a 3 MHz resolution bandwidth. The noise measurements are made using the pulsed scheme described in Ref. [19]. Postdetection noise averaging is performed over either 300 or 10^3 Q-switch laser pulses.

Figure 2 shows one of the squeezing data taken with a 3 mm long KTP crystal for measured $g_m = 16.5$. The vacuum-state noise level is recorded by simply blocking the squeezed-state input to the homodyne detector. Approximately halfway through this recording, the two detectors are blocked to obtain the electronic background noise level. Each data point in the time scan (trace labeled "Vacuum Level" and "Background Level") is a moving average over 10^3 Q-switch pulses. The vacuum-state noise level is higher than the background noise level by 12.9 dB. Since the high peak-power mode-locked pulses can easily saturate the photodetectors, the LO power cannot be increased indefinitely to shift the vacuum-state noise level far above the background noise level. Here we note that the vacuum-state noise level measured when using a coherent-state LO (IR output of the laser) of the same mean power lies within 0.1 dB of the above value. When averaging over 10^3 pulses the standard deviations in the measurement of the vacuum-state and background noise levels are 0.1 dB and 0.08 dB, respectively. After measuring the vacuum-state and background noise levels, all the beam blocks are removed to observe the squeezed-state noise. First the LO phase is scanned by applying a voltage ramp to PZT2 and recording a moving average over 300 pulses for each setting of the LO phase [triangles plotted in Fig. 2]. After the scan, the LO phase is fixed, and a time trace [labeled "Fixed LO Phase" in Fig. 2] of the squeezed-quadrature noise is recorded by averaging over 10^3 pulses at each time step. Because of the uncontrollable residual LO phase drift the squeezed-quadrature noise varies to within ±0.4 dB of the average noise minimum. The statistical error in the measurement of squeezing is the sum of the vacuum-state and background noise measurement errors (0.18 dB). From the fixed LO-phase time trace in Fig. 2 the maximum measured squeezing is 5.2 dB. After subtracting the background noise contribution this corresponds to a squeezing of 5.8 dB.

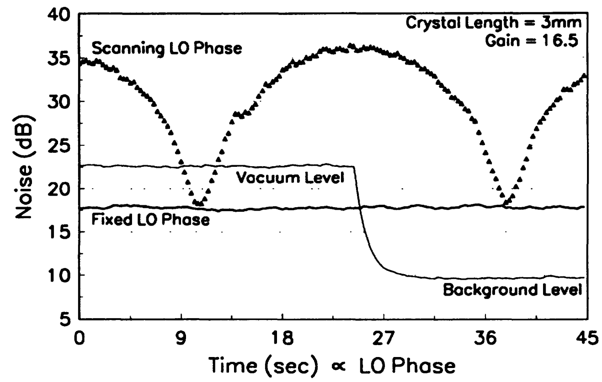

FIG. 2. An example of the pulsed homodyne-detection noise measurement using the scheme described in Ref. [19]. A 3 mm long crystal was used and the pump power was set to obtain $g_m = 16.5$. Direct output from the detection electronics is shown which recorded the photocurrent noise power at 27 MHz with a resolution bandwidth of 3 MHz. After subtracting the electronic background noise, the measured quadrature squeezing is 5.8 ± 0.2 dB.

Following the above procedure, squeezing is measured for various values of the measured DOPA gain g_m as plotted in Fig. 3. Data in Figs. 3(a) and 3(b) are for a 3 mm and a 5 mm long crystal, respectively. In both cases the solid curves are a fit by Eq. (2) with $\eta = 0.785$. In fact η was used as an adjustable parameter to fit Eq. (2) to the data. Independent measurements of propagation loss (23 optical surfaces contributing a total loss of $\simeq 10\%$), detector quantum efficiencies ($\simeq 90\%$ each), and homodyne efficiency (98.7%) confirm the above value. As shown in Fig. 3 both data sets are in good agreement with the theory, verifying that the LO is matched to the spatiotemporally distorted squeezed-vacuum state as if both the squeezed-vacuum state and the LO are single mode plane waves.

The squeezed state generated in our experiment is not an ideal squeezed vacuum because of the finite extinction ratio at the various PBS's. This is mainly because the amplified signal and idler beams from the NOPA do not spatially overlap perfectly due to the walk-off effect in the KTP crystal; walk-off precompensation, as shown in Fig. 1(b), helps but is not perfect. As the DOPA gain increases, the extinction ratio at PBS3, that between the squeezed state and the LO branches, decreases. For $g_m \simeq 20$, this ratio is $\simeq 40:1$ which at low gains is $> 160:1$. The relative noise contribution of the resulting mean field in the squeezed-vacuum branch is $1/40 = -16$ dB, which is negligible in our experiment.

In conclusion, we have experimentally demonstrated a pulsed squeezed-vacuum state generation scheme which automatically produces a spatiotemporally matched LO. Using the matched LO, we observed 5.8 ± 0.2 dB [$(74 \pm 1)\%$] of quadrature squeezing which, to the best of the authors' knowledge, is the highest observed in any traveling-wave squeezing experiment to date. In our experiment the squeezing limitation predicted in Ref. [13] is clearly circumvented.

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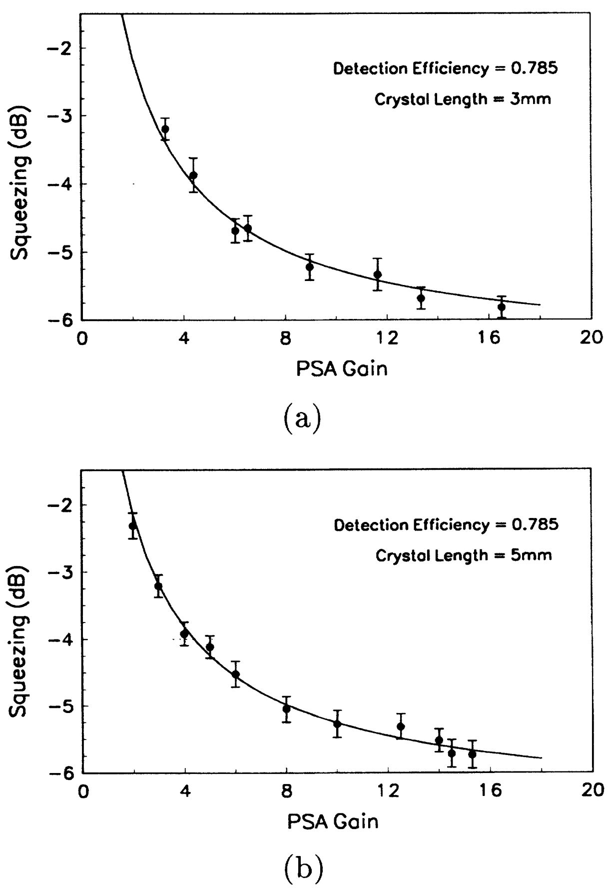

FIG. 3. Measured squeezing as a function of the measured DOPA gain g_m for the 5 mm crystal (a) and for the 3 mm crystal (b). The solid lines are plots of Eq. (2) with $\eta = 0.785$ in both cases.

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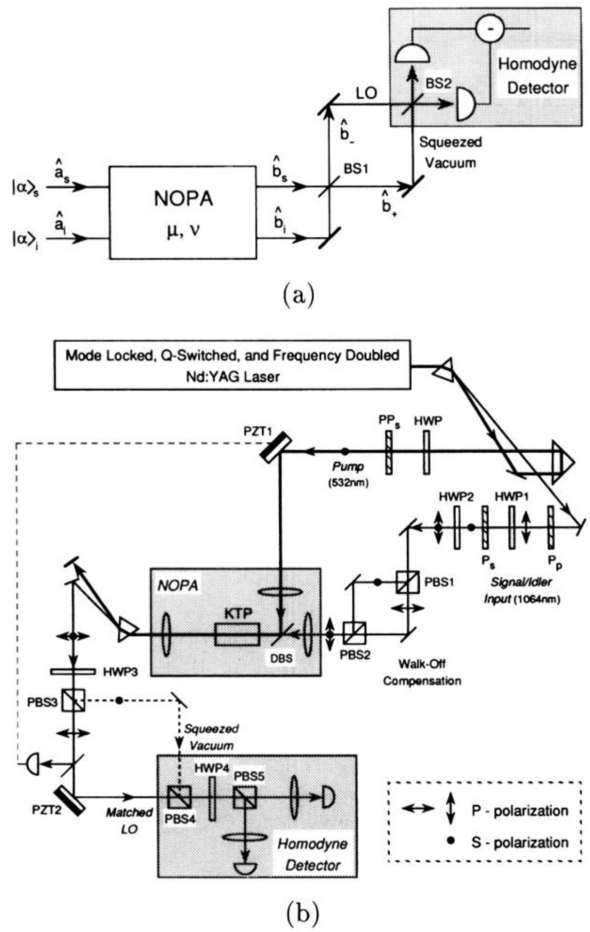

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